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HOW TO DEFINE THE ENVIRONMENTAL DIMENSION OF SUSTAINABILITY?

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ABSTRACT

Several definitions of the environmental dimension of the sustainable development exist, but they are usually quite vague, global. In addition, most of the environmental assessments do not take into account properly the variety of the environmental impacts, or are using tools which do not represent the impacts. A correct representation of the whole range of impacts is necessary to ensure that sustainability takes into account environmental issues to a satisfactory degree and in a transparent way. What are the impacts on environment? What are their characteristics or typical features? We answer to these questions by using the concept of chain of causalities, describing the process between a source and a final impact. The parameters of the chain of causalities are: the type of source, the process itself through the main scientific disciplines involved, the time and distance scales between the source and the final impact, the type of final target (nature: resources and ecosystems; humans: human health in a restricted meaning and human well-being; man-made heritage; earth covering all the targets). This analysis allows us to define 50 chains of causalities, corresponding to various public concerns. They are independent and cover all the impacts. They can be merged in different ways, but it appears that the classifications usual in economy according to quality of life / natural heritage, or present / future generations are hardly pertinent. Indeed, if the chains of causalities and the environmental impacts can be described according these axes, they are rather continuous axes than discrete or binary ones.

Key-words: Environment, impact, typology, source, process, target

INTRODUCTION

A lot of literature is today available on the concept of sustainable development. It is often presented as tridimensional (economic, social, environment) together with three other transversal dimensions: the needs, in particular the essential needs, the taking into account of the long term (future generations), and the institutional aspects (governance). If the economic side seems quite well defined (added value, income) as the taking into account of the long term, the social aspect is rarely explicit and a source of confusion: It includes sometimes all the societal aspects including the quality of life or the health impacts, but does not include always the equity between the humans. The needs are often difficult to define: nobody can tell us the limits of the needs even among the most essential ones (except the food needs), although defining the needs by the solvable demand, i.e. the income determining the amount of the needs (Rist, 2002). Finally, the meaning of the term governance is and stays very variable, not well clarified, insubstantial in many cases, but also sometimes very well designed (Hermet et al., 2005).

It is also the case of the environmental pillar, most often a vague term, referring sometimes to the quality of life, to the natural resources indispensable for life or economic activity, or to the nature.

The strong and weak concepts of sustainable development differ especially by the content of the environment. The economy-based concept of sustainability considers mainly the living environment, i.e. local and reversible nuisances produced by the economic activity and potentially eliminated by a better management. The strong concept considers rather global natural and non-renewable resources which are necessary for our well-being, and irreversible and global nuisances. In other words, noise or oil.

Thus OECD (2001) makes a difference between on the one hand the development criteria whose environmental part deals with the environmentally conditioned welfare and the health for present generation through air quality, noise, and water quality, on the other hand the sustainability criteria whose environmental part deals with the conditions of a long term development through critical natural resources, ecosystems, and climate stability. This last type of criteria is often taken into account by economists in the form of a natural capital, or more precisely of a natural heritage or a resource, because a capital is managed to be increased and an heritage to be transmitted (Godard, 1990). However, the notion of "resource management" is specific to our western societies and is not inevitably understood in the same way by other societies, although the sustainability is the core of their concerns (Rey, 2008). The pressure-state-impact (PSI) system from OECD seems well applicable to this meaning with a pressure representing a flow. It is the most common presentation of the environment, especially by economists, considering it as a resource used by the humans for producing economic goods. This resource is an ecosystem, i.e. the association between a physicochemical and abiotic (the biotope) environment and a living community characteristic of the latter (the biocenosis), including fossil resources. This resource is destroyed but can be renewed at a given extent: the environmental issue is a question of resource stock, resource flow and capacity of the biosphere to support the effects of the human activities (carrying capacity): It calls the 7th principle of the Rio declaration (UNCED, 1992): "*...to conserve, protect and restore [...] the integrity of the Earth's ecosystem [...] the pressures their societies place on the global environment*".

Perret (2005) uses a similar approach, by differentiating the flow indicators (relative to the living conditions of the present generations) and the stock indicators (relative to the conditions of a future development). For the environment, they are respectively the environmental quality and the natural capital. The distinction flow/stock is nevertheless simplistic: For instance the well-being and the environmental quality are partially transmitted and are conditions of future development; Above all this mechanistic view does not correspond always to a reality.

In parallel, the environment is often understood as the quality of our physical environment or the quality of life: a calm area with pure air and pure water, a beautiful landscape... (Job, 2005; Gudmundsson, 2007 for instance). It calls the first principle of the Rio declaration: "*Human beings [...] are entitled to a healthy and productive life in harmony with nature*". It is here often difficult to consider only flows or pressures, although some authors, as Perret (2005), consider that the flows deal with the quality of life of the present generations.

These both meanings of the environment correspond roughly to the external and internal territory sustainability by Wackernagel and Rees (1999): the internal sustainability consists in protecting its direct environment and living area, but the external sustainability consists in protecting the world.

The characteristic of all these definitions of the environment pillar of sustainability is to be synthetic, global, top-down, and not based on an explicit analysis of the environmental impacts, objectives or issues. Such definitions are much too global and rough to be useful for describing the environmental issue or the impact on the environment of a human activity, and for designing environmental impact indicators. An exhaustive list of the environmental impacts or objectives is

necessary to present a full picture, especially if the explicit aim is to identify the most important issues (Black, 2000; Borcken, 2003), and even to choose the issues of some importance for decision making (Ahvenharju et al., 2004; Nicolas et al., 2003; Zietsmann & Rilett, 2002): How to identify the important issues with a top-down approach without an encompassing assessment of all relevant issues?

When the environment is described in a detailed way, these descriptions are usually rather heterogeneous and structured in a often questionable manner.

Thus, the environmental objectives of the sustainable development, as presented for instance by Gudmundsson (2007), merge primary objectives (e.g. environmental quality), secondary objectives which should be deduced from them (use less non-renewable resource for instance), and objectives in terms of solutions (less use of private vehicles, more use of public transport for instance), without differences being perceived and the objectives being logically organized into a hierarchy.

Very often, health, safety or land-use are considered in parallel to the environment, inferring that they are not part of the environment (see for instance Wolfram, 2004, or SSNC, 2006). Droulers et al. (2008) integrate the health impacts into the social dimension and not into the environmental one, whereas the environmental dimension integrates an indicator of the concern to environment in general in comparison to other concerns, which should be rather used to weight the environmental item among others. The environmental dimension is limited to deforestation and biodiversity by lack of data (although health is taken into account otherwise), but the other aspects not taken into account are not presented: it does not allow to see if some other important items have not been left out without apparent reason.

Some authors consider that the most important is to take into account health, safety and land-use impacts, whatever it is included within the environmental or social pillar, because it does not make practical difference. If the most important is of course to take into account all the environmental impacts, even possibly to leave them explicitly out for some practical reasons, the categorisation of each impact has a political meaning, because the aggregation defines implicitly the three economic, social, and environmental issues. The citizens and often the policy makers are not able to consider the detail of the social and environmental issues and remain at the macroscopic level "social" or "environmental", for instance through indicators of the concern to environment in comparison to the social issue, to the social in comparison to economy etc, as made among others by Droulers et al. (2008). It is therefore important for the transparency of the evaluation and ultimately of the political choice that the social definition of the terms environment, social and economy does correspond to their detailed content.

Thus, Lardé and Zuideau (2008) do not justify the choice of 12 criteria they use for designing the environmental profiles of 21 countries. These criteria are measured either by source parameters (emissions), or by parameters illustrating the environmental policies. But the output, the country typology, depends without doubt on the criteria used. The 12 criteria are considered from their definition as equally important, whereas the statistical tools used discard the well correlated parameters. Thus, CO and CO₂ emissions, which are surely not well correlated, play the same role in the definition of environmental profiles, although CO is today considered as a very secondary pollutant and CO₂ as an essential pollutant, and without doubt the most important source parameter. It builds undoubtedly a typology, but we do not see easily of what. If most of the papers deal actually with environment, they deal quite never with "the" environment, concept never defined explicitly and precisely, globally: Some impacts or concerns are taken into account, others are not, without this choice being touched on and even less justified.

In the absence of precise definitions, and all the more of an agreement on a given definition, the assessment of the sustainability of a situation, a project or a policy, the evaluation *ex-ante* or the looking for the causes of an *ex-post* evaluation lend themselves to any adjustment.

Everybody interprets the concept, adapts it as widely than it remains sometimes only a vague expression without any meaning, and at worse is used only to justify his project or his policy. We saw for instance, among many other cases, the concept of "natural performance indicator" of a territory, based on the number, the surface or the diversity of the natural areas easily accessible by a resident of this territory. It is presented (Poulit, 2008) as a measurement of the environmental pillar of the sustainable development, whereas it is only a measurement of the access to the transport infrastructures. Is-it useful to specify that this indicator is widely used by the car and transport infrastructure circles?

Even if the three first pillars of sustainability are not independent, even if sustainable development should be seen not like a final state, but as a *process* (WCED, 1987), we have to define quite precisely a concept when it is used so widely than today. Otherwise, we could almost believe with George Orwell that "Political language is designed [...] to give an appearance of solidity to pure wind".

Van Assche et al. (2008) or Block et al. (2007), before defining almost 200 indicators of sustainable city for the Flemish urban areas, stress with reason on the need of defining firstly a matrix view for a sustainable and viable city, giving a normative framework for the indicator choice. They indicate afterwards that each indicator has to be connected very clearly with an item of the matrix view, what they call the pertinence criterion.

A clear distinction has to be made between impacts, issues or objectives, and indicators. Impacts, issues or objectives are criteria to be considered, but, according to the COST action *EST Towards the definition of a measurable environmentally sustainable transport* (Joumard, 2008), "*an indicator is a variable, based on measurements, representing as accurately as possible and necessary a phenomenon of interest to human beings. An environmental impact indicator is a variable based on measurements, representing an impact of human activity on the environment, as accurately as possible and necessary.*" Therefore an indicator is the tool for measuring an impacts, for taking into account an issue or to measure how an objective is achieved.

The selection or the building of indicators measuring environmental criteria requires that each process, each chain of causalities from the source to each final impact on the environment is described in detail: in terms of sources, intermediate and final targets, mechanisms between intermediate sources and intermediate targets. Such description allows us also to express clearly what a potential indicator does measure and does not measure, and on which scientific mechanisms an indicator should be based. For instance the global warming potential evaluates the global temperature increase and not really the final impacts of greenhouse effect as sea level increase, the amount of fauna, flora and human habitat destruction, the food chain changes... The knowledge of the physical mechanism of the climate and temperature modifications as a function of greenhouse gas emissions allowed to build the shape of the indicator 'global warming potential'.

At the same time, the description of the chains of causalities allows us to define quite precisely the term 'environment': What are the impacts on the environment? What are the issues, what could be the objectives? What are their characteristics or typical features?

PRECISE DESCRIPTION OF THE ENVIRONMENTAL ISSUES

In the literature

The environmental or ecological impacts are often listed in the literature (USEPA, 1996; OECD, 1996; Swedish EPA, 1996; EC, 2001; OECD, 2002; EEA, 2002; COST 350, 2002; Borcken, 2003; Ahvenharju et al., 2004; Goger, 2006 or Goger & Joumard, 2007; Joumard & Nicolas, 2009), as in public surveys at national (Boy, 2007) or international level (EC, 2008): See some examples Table 5. Their definition is neither clear nor precise. The lists are often

heterogeneous, merging sources, intermediate states of the environment as local air quality, water quality, and final impacts on the environment as visual effects. For instance USEPA (1996) or Ahvenharju et al. (2004) list mainly the pressures or the first consequences of the transport system on the environment rather than environmental impacts (although designed as impacts). Beside some impacts quite always mentioned as climate change, photochemical pollution or noise, some others are rarely mentioned as soil erosion, vibration, light pollution, hydrologic and hydraulic risks, odours, soiling or visibility. Dimming, fire risk or electromagnetic pollution are not mentioned at all in the 13 references studied. Some impacts listed are very wide, merging several impacts on the environment, as air pollution or protection of soil and landscape. Some lists, as this one of the European directive (EC, 2001), list the final targets but some are redundant as biodiversity / fauna and flora, population / human health. Goger (2006) or Goger & Joumard (2007) give the most precise list but only due to atmospheric pollutant emissions: In this field, impacts are distinguished when they are due to different chains of causalities, taking into account the fact that the impact categories shall together enable an encompassing assessment of relevant impacts, which are known today (completeness), but at the same time should have the least overlap as possible (independence).

In addition, the content of each chain of causalities depends on the society where it appends. Esoh Elame (2004) for instance shows how the values and beliefs of the cultural heritage of given African peoples determine in a large extent the items of the nature they want to protect; In Black Africa, the natural capital can not be dissociated from the cultural capital: To speak about nature means to speak about culture and vice-versa. Similar relationships had been shown by Roqueplo (1988) or Brüggemeier (2002) in the case of forests and acid rains in Germany. More generally Lammel & Resche-Rigon (2007) show how the concept of environment itself differs between holistic societies as Totonaque, Inuit or Badui ones and individualist / analytic societies as the Western ones.

In the Western countries at least, the environment is basically a personal construction, based on the personal perception of its issues, through our perception by our senses (sight, smell...), completed by intellectual elements coming from technical or scientific news we receive through the education system and the media (Brüggemeier, 2002 ; van Staëvel, 2006). This personal construction is then structured by a long-term view. Thus for 65 % of the French people in the 21st century the technical progress will be subjected to a sustainable development (Maresca & Hebel, 1999), i.e. transmitting to the future generations a viable environment and a nature not deserted.

A survey made for the European Commission on 26 730 Europeans face to face at the end of 2007 gives information on the meaning of the term environment and on the main issues for the citizens (EC, 2008). The meaning of the term and the issues depend on the country and change with time. The citizens of the new member States seem less sensitive to the climate change than those of old ones, but distinctly more sensitive to nature issues. The French are noticeable by the importance they give to the using up of natural resources and the agricultural pollution. Globally, the Europeans are more and more concerned with the climate change, which is the main environmental issue.

One of the most structured description of the environment consists of streamlining the problem through objectives as proposed by Keeney (1992). Rousval (2005) and Rousval and Maurin (2008) applied this method to the environment, and got a hierarchy of goals by interviewing a limited number of local decision makers and environment specialists: See the output Table 1. This list is nevertheless rather heterogeneous, merging final targets (fauna, flora), processes (greenhouse effect) and intermediate impacts (soil pollution). It has the main advantage, as the approach of Van Assche et al. (2008) or Block et al. (2007), to use a systemic approach, with a clear logic.

Table 1: *Hierarchy of objectives in the environmental field according to Rousval (2005) or Rousval and Maurin (2008).*

| |
|--|
| <p>Master the environment</p> <p>At global scale</p> <ul style="list-style-type: none"> Preserve an environment in favour of the human life <ul style="list-style-type: none"> Limit the greenhouse effect Limit the climate change Protect the ozone layer Preserve the natural resources <ul style="list-style-type: none"> Limit the extinction of natural species Limit the extinction of natural environment Limit the energy consumptions Limit the maritime pollution Limit the production of non-recyclable waste <p>At local scale</p> <ul style="list-style-type: none"> Concerning the natural environment <ul style="list-style-type: none"> Limit the soil degeneration Protect fauna Protect flora Preserve landscapes Limit the excessive concreting Concerning the human environment <ul style="list-style-type: none"> Concerning the public health <ul style="list-style-type: none"> Limit the effects of air pollution <ul style="list-style-type: none"> Of the pollution peaks Of the background pollution Limit the effects of the hazards Limit the health impacts of noise Concerning the quality of life <ul style="list-style-type: none"> Limit the annoyance <ul style="list-style-type: none"> Due to noises Dues to fumes Dues to odours Improve the townscape Preserve the cultural legacy Respect the areas « villages » Preserve habitats from soiling |
|--|

The concept of chain of causalities

With the aim to use a systemic approach of the environmental issues, encompassing all the environmental impacts and all the potential objectives of an environmental policy, we propose to enlarge the pressure-state-impact structure to the concept of process or chain of causalities between a cause and a final impact, with possibly a succession of couples cause-impact. A good example is the greenhouse effect with the greenhouse gases emission (GHG) as a first cause, which by physical phenomenon increases the earth temperature, which modifies the global and local climates, with impacts on the agriculture, sea level, with impacts on all the biocenosis including the humans. If an initial pressure can be easily detected (GHG emissions), there are afterwards a lot of intermediate states and impacts.

Table 2: Typology of the main transport subsystems. Colours correspond to wider subsystems as used in Table 6.

| | | | | | |
|--|-----------------|--------|----------------------------------|---------|------------------|
| Infra-structure | building (1) | Energy | final electricity production (5) | Vehicle | production (9) |
| | existence (2) | | electricity distribution (6) | | existence (10) |
| | maintenance (3) | | fuel production (7) | | maintenance (11) |
| | destruction (4) | | fuel distribution (8) | | destruction (12) |
| Traffic = infrastructure - final energy - vehicle use (13) | | | | | |

Table 3: Typology of the targets of the impacts on the environment.

| Targets | | Pseudo-target |
|--|--|--|
| Nature | Resources | Earth: Covers all the targets: the three previous targets (ecosystems, humans and man made heritage) and physical environments such as the atmosphere and the oceans |
| | Ecosystems: Nature understood as ecosystems, i.e. the association between a physicochemical and abiotic (the biotope) environment and a living community characteristic of the latter (the biocenosis) | |
| Humans: Humankind which we extract from nature and focus on its health as defined by the WHO | Human health: In a restricted meaning | |
| Human well-being | | |
| Man-made heritage: With a distinction is made between common and historic buildings | | |

Another advantage of the concept of process or chain of causalities is to be much wider than a stock or flow problem inspired by physics: any process can be taken into account, as cultural, psychological, psycho-physical, biological effect, and of course physical. A chain of causalities can be described through:

- The element(s) of a field of human activity (the transport system or any other sector), which is at the begin of the process, taking into account the life cycle approach, ie. considering all the sub-activities involved. In the case of transport sector, we are focussing on, three main subsystems are involved (infrastructure, energy used, and vehicle), and for each of them five types of activities (production, existence, use, maintenance, destruction). All together there are 13 subsystems-activities, as the use of the infrastructure, final energy and vehicle is considered common to the three subsystems (i.e. the traffic): See Table 2. The 13 subsystems can be simplified into four, as coloured in Table 2 and used in Table 6, by considering the three main subsystems but extracting the traffic.
- The final targets: Goger (2006) and Goger & Joumard (2007) consider three targets (nature, humans, man-made heritage) and a pseudo-target, the earth. In addition the Eco-indicator approach (Brand et al., 1998; Goedkoop & Spriemsma, 2000) includes three types of endpoint damages: resources, ecosystem quality, and human health. The two first are subdivisions of

the target nature. The (human) health is defined by World Health Organisation (WHO, 1946) as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*". Therefore it is useful to distinguish health in a restricted meaning (absence of disease or infirmity) and the complement so-called human well-being, because the processes are often very different. Finally we get the target structure presented Table 3, with six targets: the resources, the ecosystems (both together the nature), the human health in a restricted meaning, the human well-being (both together the humans or the human health as defined by WHO), the man-made heritage, the earth.

- The in-between elements, i.e. the chain of causalities between the human activity (as the transport system) and the final targets, to be described in detail. To design impact indicators, it is important to know the scientific milieu able to understand the process, and therefore to give the scientific disciplines involved. We propose a first and simple science structure: physics, chemistry, biology, psychology/sociology. It is important also to know if the process is linear or not, and if the human activity characteristics are major or minor explanation parameters, in order to know how these characteristics can be used for indicator building. Finally the reversibility is a major parameter from the sustainability point of view; The distance and time scales indicate who is concerned, if it is a local/global, short/medium/long term impact.

Description of the chains of causalities

The whole picture disaggregates the different impacts found in the literature in order to understand the complexity of the processes involved, to identify the related sciences and to estimate the order of magnitude of the impact in space and time.

According to this structure, a typology of the chains of causalities of the environmental impacts (especially due to the transport system) is proposed Table 6. 49 chains are distinguished, taking into account the source, the process and the final target as described above. The 49 chains, briefly described Table 6, are independent and encompass all the relevant impacts found in the literature.

The description of the chains could be more detailed, by dividing a chain into two or more chains, if it is considered as not homogeneous in terms of process or targets. In addition some chains can be missing.

A first attempt to build a typology or structure of the 49 chains of typology is made. They are merged firstly into 27 aggregated chains, mainly by not considering the final target, and then into 8 groups (see Table 4). This typology corresponds mainly to usual structures and allows a simpler presentation of the whole structure.

Back to the top-down approach

The aggregation of impacts is always possible. It could be useful to design impact indicators, for instance when the scientific knowledge necessary to build indicators of different impacts is similar and if the main characteristics of the corresponding chains are also similar. As, to be practical, the number of categories should amount to a not too high number, and considering the importance of each impact and the availability of indicators, some impacts could be merged, or chains considered as minor could be deleted. Because it is important to give the possibility to further users to perform such simplifications, the chain structure has to be as detailed as possible: It is easier to merge and delete than to add processes.

How do stand the 49 chains of causalities we defined above in the global descriptions of the environment pillar of sustainable development seen above? These ones belong finally to two types:

- According to the axis life environment / natural resource, with two sub-categories:

- A1 The well-being, the quality of life
- A2 the resources needed for life, the natural heritage, the sustainability
- According to the axis present / future generations, with two sub-categories:
 - B1 Present generations
 - B2 Future generations

Table 4: *Hierarchy of the 49 chains of causalities*

. Noise and vibrations

- . Noise:
 - . Disappearance of quiet areas (chain 1)
 - . Annoyance to people due to noise (chain 2)
 - . Effects on human health (restricted meaning) of noise (chain 3)
 - . Effects on animal health of noise (chain 4)
- . Vibration (chain 5)

. Traffic safety

- . Human traffic safety (chain 6)
- . Animal collision: Animal fatalities (chain 7)

. Air pollution

- . Sensitive air pollution
 - . Odours (chain 8)
 - . Soiling (chain 9)
 - . Visibility (chain 10)
- . Direct (restricted) toxicity of air pollutants
 - . Direct restricted effects on human health of air pollutants (chain 11)
 - . Direct ecotoxicity on fauna and flora of air pollutants (chain 12)
- . Photochemical pollution
 - . Health effects of photochemical pollution (chain 13)
 - . Loss of crop productivity due to photochemical pollution (chain 14)
 - . Ecotoxicity on fauna and flora of photochemical pollution (chain 15)
 - . Loss of cultural legacy due to photochemical pollution (chain 16)
 - . (Secondary effects: greenhouse gas, acidification)
- . Acidification
 - . Decrease of ecosystem health, loss of biodiversity due to acidification (chain 17)
 - . Deterioration historical buildings and other cultural assets due to ac. (chain 18)
- . Eutrophication (chain 19)
- . Dimming (chain 20)
- . Ozone depletion
 - . Health effects of ozone depletion (chain 21)
 - . Ecotoxicity on fauna and flora of ozone depletion (chain 22)

. Soil and water pollution

- . Pollution of soil, surface waters and groundwater
 - . Effects on ecosystem health of pollution of soil, surface waters and groundwater (chain 23)
 - . Health effects of pollution of soil, surface waters and groundwater (chain 24)
 - . Recreational areas forbidden due to pollution of soil and surface waters (chain 25)
- . Maritime pollution
 - . Effects on ecosystem health of maritime pollution, including habitat disruption by wakes / anchors (chain 26)
 - . Health effects of maritime pollution (chain 27)
 - . Recreational areas forbidden due to maritime pollution (chain 28)
- . Hydraulic changes and risks
 - . Hydraulic changes (chain 29)
 - . Hydraulic risk (chain 30)

- . **Impacts on land**
 - . Land take
 - . Loss of natural habitats due to land take (chain 31)
 - . Degradation of ecosystems, loss of biodiversity, including when due to biofuel agriculture, due to land take (chain 32)
 - . Modification of outdoor recreation areas, due to land take (chain 33)
 - . Loss of cultural legacy, due to land take (chain 34)
 - . Habitat fragmentation
 - . Loss of ecosystem health, loss of biodiversity, due to habitat fragmentation (chain 35)
 - . Reduction of living areas of people, due to habitat fragmentation (chain 36)
 - . Soil erosion (chain 37)
 - . Visual qualities of landscape/townscape (chain 38)
- . **Non-renewable resource use and waste handling**
 - . Non-renewable resource use (chain 39)
 - . Non-recyclable waste (chain 40)
 - . Direct waste from vehicles (chain 41)
- . **Greenhouse effect** (chain 42)
- . **Other impacts**
 - . Electromagnetic pollution
 - . Health effects of electromagnetic pollution (chain 43)
 - . Effects on ecosystem health of electromagnetic pollution (chain 44)
 - . Light pollution (chain 45)
 - . Introduction of invasive alien species (chain 46)
 - . Introduction of illnesses (chain 47)
 - . Fire risk (chain 48)
 - . Technological hazards (chain 49)

When classifying our 49 chains of causalities according to A1/A2 or according B1/B2, some chains cannot be differentiated according to such binary classification, belonging to both classes. In the same manner, most of the 27 aggregated chains are aggregating detailed chains belonging to both categories. Therefore it is evident that these global classifications are not pertinent, because they cannot be used for characterizing some chains of causalities. The reality is definitively more complex than the globalising approaches.

The chains of causalities can also be described according to their local or global character, or according to their time scale (short / long term), quite close to the reversible character (reversible / irreversible). But here again, as it can be seen in Table 6, these axes are rather continuous. Thus, the geographical scale goes from the very local (some hundred of meters for the odours) to the global level (the whole earth for the greenhouse effect), but with intermediate scales as for the photochemical pollution (a thousand of km). We have the same picture for the time scale: Between the very short term (an hour for the odours or the hypoxic effect of carbon monoxide) and the very long term (some thousands of years for the impacts of some nuclear waste), we have impacts with middle time scales as the photochemical pollution (a day), the soiling or hydraulic risks (a year)... The irreversible character has to be firstly defined according to its aim: The traffic safety has irreversible impacts for the humans who die, but for the society it is a reversible impact. If we consider only the irreversible character for the society, i.e. the definitive modification of our life conditions on the earth, here again the dichotomy reversible / irreversible is only apparent: Several chains of causalities, and not the least ones, are neither totally reversible nor totally irreversible. Thus the greenhouse effect is well reversible, but only after some centuries: It is totally reversible at the cosmic scale, but irreversible at the human scale.

CONCLUSION

To describe the environmental impacts of an activity as transport through a complete list of independent chains of causalities allows us firstly to give a precise definition of the term 'environment'. In the literature, the differences in the impacts considered translate often the research area of the author, and, when the work is more global, the local perception of the environmental or ecological issue. For instance the loss of visibility above the cities, due to air pollution, is often cited in North America, but never in Europe, although the physical situations are similar. It is especially important to define the term environment, when today the environmental issue is widely taken into account but without a precise knowledge of this field: In this case the environmental issue is very often reduced to greenhouse gases or to few well known impacts, or are reduced unconsciously to impacts for which simple to use assessment tools are available.

Environmental impacts, environmental issues, environmental objectives are not equivalent expressions. The chains of causalities we have defined and described deal clearly with environmental impacts. Following Keeney (1992), environmental objectives are characterized by three features: a decision context (who does decide, what to decide?), an object (an environmental impact or an aggregation of impacts), and a direction of preference (decrease the environmental impact). Nevertheless, as shown by Rousval (2005) (see Table 1), the environmental objectives can be quite easily linked to environmental issues, and then to environmental impacts, or to aggregations of impacts or of chains of causalities. The typology of chains of causalities can therefore be used as a basis to describe environmental issues and environmental objectives. However, in most of the cases, the list of chains of causalities we propose here is much too detailed to be used in a decision context: The chains have to be aggregated, or some of them have to be chosen and others left aside. The knowledge of a comprehensive list allows to aggregate and choose with full knowledge of the facts. It is also a comprehensive basis to study the social perception of the environmental issue by survey, whom outputs can be used to balance the quality of local air, of regional air, noise, greenhouse effect... according to the focus placed on each of these impacts, as made for instance by the Personal Security Index designed by the Canadian Council on Social Development (Tsoukalas & MacKenzie, 2003).

The framework of the chains of causalities should be an universally valid analytical framework. It is surely not the case, because some generally marginal but possibly locally important impacts can be forgotten and should be added. In concrete assessment situations, this overarching concept can be adapted by leaving explicitly some impacts out, for instance because they are not pertinent or by lack of data: The most important is to do that explicitly. The main limit of the framework is cultural: it is certainly adapted to Western societies, but could be not adapted to Eastern, African or other societies, where the concept itself of environment can be fundamentally different or does not exist in this shape.

The social context plays therefore a role in the construction of the framework of the chains of causalities. This context is also especially important when taking into account the three pillars of the sustainable development. What is our concern to environment in comparison to the social or economic issue? Public inquiries or inquiries specific to a given circle allow to answer such questions, but the meaning of each pillar has to be clear: The detailed description of the environmental chains of causalities should be of some help, possibly after aggregation or simplification, to make explicit the meaning of the environmental pillar.

The precise description of the environmental processes constitutes then a powerful tool for indicator assessment, similar to but more completed than that done by USEPA (1996). *A priori*, it can be stated that the nearer to the final target the indicator is, the more precise the final impact is estimated. It is mainly a tool to define what precisely an indicator does represent: Does it

represent the final impact, or an intermediate one? How accurately is the process translated into the indicator function? Which relevant impacts are not taken into account by existing indicators? Isn't it possible double counting? When the business is not only, in the name of the pragmatism, to reorganise already existing information, but to build the tools necessary to measure really the environmental impacts, the encompassed description of the impacts is the first step of the process. When the aim is to design new indicators for instance of environmentally sustainable transport, the knowledge of the process indicates which scientists should be asked about the best way to represent the impact.

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| | | | | | | | | |
|---------------------------------|-----------------------------|--|--|-------------------------------|-------------------|--|-----------------------------------|---|
| | pollutant emissions | | | | | | All impacts from transport | USEPA (1996) |
| | photochemical pollution | damages to agriculture | health effects due to local & regional pollution | stratospheric ozone depletion | greenhouse effect | use of non renewable resources | | OECD (1996) |
| eutrophication of water | photochemical oxidants | urban air pollution, effects of metals, effects of POP | | depletion of ozone layer | greenhouse gases | | | Swedish EPA (1996) |
| water | air, human health | | | | climatic factors | | | EC (2001) |
| water quality | air quality | | | | climate change | use of natural resources | | All impacts from transport OECD (2002) |
| | photochemical smog | | human health | | climate change | | energy consumption | EEA (2002) |
| water pollution | air pollution | | | ozone depletion | climate change | use of material resources | non-renewable energy consumption. | From transport (red: global; black: local/regional) COST 350 (2002) |
| | photosmog | ecosystem health | human health | stratospheric ozone depletion | climate change | consumption of (energy) resources | | Borken (2003) |
| | emissions of air pollutants | | | | greenhouse gases | consumption of solid raw materials | energy consumption | Ahvenharju et al. (2004) |
| eutrophication | photochemical pollution | Direct ecotoxicity | direct restricted health effects | ozone depletion | greenhouse effect | | | impacts due to pollutant (grey: out of the scope) (2006), Goger & Joumard |
| water quality / uses and régime | regional air quality (smog) | local air quality | | | greenhouse effect | non-renewable resource use, including energy | | From transport (red: irreversible; black: reversible) Joumard & Nicolas (2009) |
| water pollution | air pollution | | | | climate change | | | Boy (2007) |
| water pollution | air pollution | | | | | depletion of natural resources | | EC (2008) |
| 5 | 18, 19, 20, 21 | 3 | 4 | 16, 17 | 49 | 22 | | Corresponding chain in Table 4 and 6 |

Table 5: Environmental impacts as listed by 12 references, and correspondence with the list of processes proposed in this paper.

| | | | | | | | | | | |
|---------------------------|----|---|-------|----------------------------------|-----------------------------|------------------------------|----------------|------------------|---|----------------------------|
| noise | | direct waste from vehicles | waste | | | release of deicing compounds | sewage dumping | | toxic release | highway and airport runoff |
| ambient noise | | | | | | | | | | |
| noise | | non-cyclic material flows, waste and environmental hazardous residues | | | nitrogen saturation of soil | | | | | |
| | | | | soil | | | | | | |
| noise | | | | | | | | | | |
| noise | | waste | | | | | | | illegal and accidental discharge of oil by ships at sea | |
| noise nuisance/vibration | | waste production | | soil erosion | soil pollution | | | | | |
| noise | | | | protection of soil and landscape | | | | | | |
| noise | | waste | | | | | | | discharges of oil, wastewater and waste at | runoff pollution |
| | | | | | | | | | | |
| light and noise nuisances | | | | | | | | | | |
| noise | | family waste, (nuclear risk?) | | | | | | | | |
| noise pollution | | growing waste | | | | | | | | |
| 33, 34, 35, 36 | 48 | 41 | 24 | 8 | 28, 29, 30 | | 9 | 25, 26, 27 | 28, 29, 30 | |

| | | | | | | | | | | |
|--|---|---|---|---------------------|----------------------------|--|---|--------------------------|-------------------|----|
| | | | | | | habitat disruption and land take by infrastructure | roadkill, wildlife collisions | | | |
| perturbation of regional ecosystems | | damages to equipments | negative aesthetic effects | | | landtake | perturbation of regional ecosystems | | | |
| areas of special conservation | | | | | | exploitation of land & water | | | | |
| fauna and flora, biodiversity | including architectural and | material assets | landscape | | | | | | | |
| historical / archaeological / nature conservation | | | visual impacts | | | | severance | | | |
| | | | | | | landtake | fragmentation of ecosystems and habitat | | safety | |
| | landscape / visual effects / aesthetics / cultural heritage | | | | hydrologic/hydraulic risks | land uptake | barrier effects / land fragmentation | | traffic accidents | |
| | | | protection of nature and landscape | | | | protection of nature and landscape | | | |
| nature areas, proximity of tr. infras. to designated | | | | | | hardening of surfaces | fragmentation of land | collisions with wildlife | light emissions | |
| | degradation of historic man-made heritage | degradation of common man-made heritage | | sensitive pollution | | | | | | |
| biodiversity and protected areas | man-made heritage | | visual qualities of landscape/townscape | | | landuse | | | traffic safety | |
| faune & flora degradation | | | landscape degradation | | | | | | | |
| | | | | | | | | | | |
| 11 | 13 | 2, 13, 31 | 47 | 44, 45, 46 | 31 | 10, 12 | 6, 7 | 42 | 23 | 15 |

| | | | | | | |
|----------------|---------------------------------------|--|-----------------------------------|---------------|---------------------------------|----------------------|
| - | habitat disruption by wakes / anchors | introduction of non-native species | hazardous material incident | | | |
| - | | | | acidification | | |
| - | | introduction and spread of alien organisms | | | acidification of water and soil | |
| - | | | | | | |
| - | | | | acidification | | loss of biodiversity |
| - | | | | | | |
| - | | | | | | |
| - | | | | acidification | | |
| - | damage of underwater habitats | introduction of non-native species | polluting transport accidents | | | |
| - | | | | acidification | | (direct ecotoxicity) |
| - | | | technological and natural hazards | | | |
| - | | | nuclear risks | | | |
| - | | | natural & man made disasters | | | loss in biodiversity |
| 37, 38, 43, 50 | 40 | 39 | 32 | 2 | 1 | 10, 14 |

Table 6: Proposed list of the main chains of causalities of environmental impacts with some characteristics.

| Sources | | | | First step of the chain (pressure) | N. Identification | Irreversibility for individuals (II) or species (IS), distance and time scale from the source to the final impact | Chain of causalities (states and processes) and final impact (main scientific disciplines involved: P: Physics; C: Chemistry; LS: life sciences; HS: human and social sciences) | n chain | Target: Resource, EcoSystem, Health, Human |
|----------------|--------|---------|---------|---|--------------------------------------|---|---|---------|--|
| Infrastructure | Energy | Vehicle | Traffic | | | | | | |
| ** | | | *** | Emission of noise | I. Noise | km, hour | Diffusion (P), disappearance of quiet areas (HS) | 1 | Well Being, MAB, made heritage, Earth |
| | | | ** | Emission of vibration | II. Vibration | 100 m, hour | Heavy traffic (HDV, trains) vibrations, mass diffusion, damage to buildings (P), annoyance to people (HS) | 2 | ES |
| | | | *** | Accidents | III. Traffic Safety | II, m, - | Human fatalities and injuries (LS) | 3 | ES |
| | ** | | *** | Emission of VOC | IV. Sensitive air pollution | 100 m, hour | Odours: Dispersion in the atmosphere (P) at short distance, sensitive pollution perceived by smell (HS) | 4 | HWB |
| | * | | ** | Emission of PM | | 100 m, year | Soiling Dispersion in the atmosphere (P) at short distance, deposition on surfaces (P), chemical reactions with materials (C), sensitive pollution perceived by the sight (HS) | 5 | HWB |
| | * | | ** | Emission of PM and atmospheric pollutants | | 100 m, day | Visibility: Dispersion in the atmosphere (P) at mid distance, chemical reaction in air (C), sensitive pollution perceived by the sight (HS) | 6 | HWB |
| | * | * | *** | Emission of particles and air pollutants | V. Direct toxicity of air pollutants | II, possible IS, km, day | Dispersion in the atmosphere and water (P), sometimes dispersion in food (P), | 7 | H |
| | | | | | | | direct restricted health effects (LS) | 8 | ES |
| | | | | | | | direct ecotoxicity on fauna and flora (LS) | 9 | ES |

| | | | | | | | | | | |
|--|----|---|-----|---|---|--|---|---|----|---------|
| | | | | | | | | <i>health effects</i> (LS) | 13 | H |
| | | | | | | | | <i>loss of crop productivity</i> (LS) | 14 | R |
| | | | | | | | | <i>ecotoxicity on fauna and flora</i> (LS) | 15 | ES |
| | * | * | *** | Emission of NOx, NMVOC, CO. | VI. Photochemical pollution | II, possible IS, IS for cultural legacy, Mm, day | Dispersion in the atmosphere (P), chemical reaction (C) and therefore increase of photochemical pollutants as ozone, | deposition on surfaces (P), chemical reactions with materials (C), loss of man-made heritage (HS), destruction of archaeological, classical or historic remains (P), <i>loss of cultural legacy</i> (HS) | 16 | M |
| | | | | | | | | Secondary effects: - greenhouse gas (see <i>greenhouse effect</i>) - acidification (see <i>acidification</i>) | - | (ES, M) |
| | * | * | *** | Emissions NOx, SO ₂ | VII. Acidification | II, possible IS, Mm, year | (incl. secondary effect of photochemical pollution) Dispersion in the atmosphere (P), possibly wet and dry deposition, chemical reaction (C) and therefore formation of acid compounds, | dispersion in air, water and soil (P), ecotoxicity on fauna and flora (LS). <i>Decrease of ecosystem health, loss of biodiversity</i> | 17 | ES |
| | | | | | | | | deposition on surfaces (P), chemical reactions with materials (C). <i>Loss of man-made heritage</i> (HS), <i>destruction of archaeological, classical or historic remains</i> (P), <i>loss of cultural legacy</i> (HS) | 18 | M |
| | * | | *** | Emissions NOx | VIII. Eutrophication | II, possible IS, 10 km, year | Dispersion in the atmosphere and water (P), increase of plant biomass (LS), <i>anoxia of fauna and flora</i> (LS) | | 19 | ES |
| | ** | * | *** | Emission of aerosols | IX. Dimming | 100 km and earth, day to month | Dispersion in the atmosphere (P), physical reactions (P) and sometimes chemical reactions (C), regional dimming, regional temperature decrease, global climate changes, <i>destruction or modification of habitat for fauna, flora and humans</i> (P), <i>change in food chain</i> (LS), <i>economic losses</i> (HS)... | | 20 | E |
| | | | * | Emission of halogen compounds | X. Ozone depletion | II, earth, year | Dispersion in the atmosphere (P), chemical reaction (C) depletion of ozone layer, increase of UV on the earth (P), | <i>health effects</i> (LS) | 21 | H |
| | | | | | | | | <i>ecotoxicity on fauna and flora</i> (LS) | 22 | ES |
| | * | | * | Emission of gaseous, liquid or solid pollutants | XI. Pollution of soil, surface waters and groundwaters | II, possible IS, 100 km, year | Dispersion in the soil and water (P), | <i>ecosystem health</i> (LS) | 23 | ES |
| | | | | | | | | <i>health effects</i> (LS) | 24 | H |
| | | | | | | | | <i>recreational areas forbidden</i> (HS) | 25 | HWB |
| | * | | ** | Emission of liquid or solid pollutants | XII. Maritime pollution | II, possible IS, 100 km, year | Dispersion in the sea (P), | <i>ecosystem health</i> (LS) | 26 | ES |
| | | | | | | | | <i>health effects</i> (LS) | 27 | H |
| | | | | | | | | <i>recreational areas forbidden</i> (HS) | 28 | HWB |

| | | | | | | | | | | | |
|-----|---|----|-----|--------------------------------------|--|---------------------------------------|--|---|------------------------------|------------|----|
| *** | | | | Land take, floods | XIII. Hydraulic changes and risks | II, possible IS, km, year | Hydraulic changes, | <i>modification of fauna, mainly, and flora habitat (P, LS)</i> | 29 | ES | |
| | | | | | | | Hydraulic risks, | <i>destruction of natural and human habitat (P)</i> | 30 | ES | |
| *** | * | * | | Land take by infrastructure building | XIV. Land take | II, possible IS, km, year | Waterproofing of areas, <i>loss of natural habitats (LS)</i> | | 31 | ES | |
| | | | | | | | Waterproofing of areas, <i>degradation of ecosystems (P, LS). Loss of biodiversity, including when due to biofuel agriculture</i> | | 32 | R?, ES | |
| | | | | | | | Waterproofing of areas, <i>loss of available land for humans, modification of outdoor recreation areas (SS)</i> | | 33 | HWB | |
| | | | | | | | Destruction of archaeological, classical or historic remains (P), <i>loss of cultural legacy (HS)</i> | | 34 | M | |
| *** | | | * | Land take | XV. Habitat fragmentation | II, possible IS, km, year | Cutting of the fauna habitat (LS). <i>Loss of ecosystem health, loss of biodiversity</i> | | 35 | ES | |
| | | | | | | | Cutting of the human habitat, <i>reduction of living areas of people (LS, HS)</i> | | 36 | HWB | |
| * | | | | Land take | XVI. Soil erosion | II, possible IS, km, year | Transformation of natural areas, <i>decrease of ecosystems (P, LS). Loss of biodiversity</i> | | 37 | ES | |
| *** | | | | Land use | XVII. Visual qualities of landscape/townscape | IS, km, year | Infrastructure presence, <i>annoyance (HS)</i> , especially if the landscape is of high quality | | 38 | HWB | |
| * | * | * | *** | Non-renewable resource use | XVIII. Non-renewable resource use | IS, Mm, 100 years | <i>Decrease of metals, fossil fuels availability for the future (P)</i> | | 39 | R | |
| ** | * | ** | | Waste disposal | XIX. Non-recyclable waste | II, possible IS, (nuclear waste), all | Includes the nuclear waste. Dissemination in the nature (P), <i>impacts on health and ecosystems (LS)</i> | | 40 | ES, H, HWB | |
| | | | * | Emission of waste | XX. Direct waste from vehicles | 100 m, year | Waste thrown directly from the vehicles, accumulation. <i>Annoyance (HS)</i> , especially if the landscape is of high quality | | 41 | HWB | |
| * | * | * | *** | Emission of air pollutants | XXI. Greenhouse effect | II, IS, earth, century | Dispersion in the atmosphere (P), sometimes chemical reaction (C) and therefore creation of secondary pollutants, increase of the greenhouse effect (P), climate change (P), sea level increase (P), <i>destruction or modification of habitat for fauna, flora and humans (P), change in food chain (LS), economic losses (HS)...</i> | | 42 | E | |
| * | | | * | Emission of waves | XXII. Electromagnetic pollution | II, km, year | Diffusion in the atmosphere, absorption or reflection by surfaces (P), | | <i>health effects (LS)</i> | 43 | H |
| | | | | | | | | | <i>ecosystem health (LS)</i> | 44 | ES |
| ** | | | ** | Emission of light | XXII. Light pollution | Possible II, Mm, min | Modification of the luminosity of the open space (P), modification of the biota behaviour (LS), <i>effects on biota health</i> | | 45 | ES | |

| | | | | | | | | | |
|---|----|--|----|-------------------------------------|---|--|--|----|------------|
| | | | ** | Introductions of non-native species | XXIV. Introduction of invasive alien species | IS, earth | Small individuals, seeds... disperse and survive (LS), modification of biocenosis. <i>Loss of biodiversity</i> | 46 | ES |
| * | | | * | Transmission of pathogens | XXV. Introduction of illnesses | km, year | The traffic itself introduces pathogens through people and goods, <i>health effect and impact on ecosystem health</i> | 47 | ES, H |
| | | | * | Risk of fire | XXVI. Fire risk | II, possible IS, 10 km, year | Fire ignition by sparks, matches... or accidents. <i>Destruction of natural and human habitat (P)</i> | 48 | ES, H, HWB |
| | ** | | ** | Industrial accidents | XXVII. Technological hazards | II, possible IS, km to earth, day to century | Industrial accidents, included of nuclear power plants. Dispersion in the atmosphere, soil and water (P), <i>biological impacts on humans and biota (LS)</i> | 49 | ES, H |